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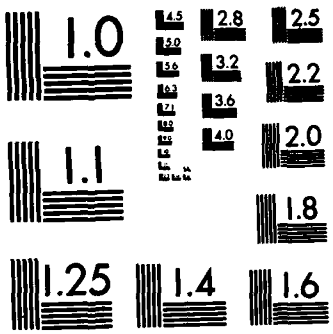

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ELECTRON IRRADIATION EFFECTS IN EDGE-DEFINED FILM-FED GROWTH RIBBON SILICON

A.E. JAWOROWSKI, G.S. OEHRLEIN[1] and J.W. CORBETT

Institute for the Study of Defects in Solids
Department of Physics, State University of New York at Albany
Albany, New York 12222, U.S.A.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Schottky diodes were fabricated on EFG (edge-defined film-fed growth) one ohm-cm p-type silicon ribbon samples, which were then irradiated with two MeV electrons at near room temperature (∿290 K or ∿310) and were studied using conventional capacitance transient (DLTS) techniques.
Several majority carrier traps were consistently observed. The thermal stability of these centers was determined by isochronal annealing studies. Tentative identifications, based primarily on comparison with energy levels and thermal stability of defects previously observed in aluminum- or boron-doped and

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) electron-irradiated silicon are as follows: $E_v + 0.165$ eV, Aℓ-related; $E_v + 0.295$ eV, vacancy + oxygen + boron, $E_v + 0.39$ eV, carbon-interstitial + carbon-substitutional; $E_v + 0171$ eV, Fe-related. Samples irradiated at ∿290 K showed the energy level of the carbon-interstitial which anneals out at 300 K within a few hours and at the same time the carbon-interstitial + carbon-substitutional peak grows, which confirms that peak identification.

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A.E. JAWOROWSKI, G.S. OEHRLEIN[1] and J.W. CORBETT

Institute for the Study of Defects in Solids
Department of Physics, State University of New York at Albany
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Schottky diodes were fabricated on EFG (edge-defined film-fed growth) one ohm-cm p-type silicon ribbon samples, which were then irradiated with two MeV electrons at near room temperature (∿290 K or ∿310) and were studied using conventional capacitance transient (DLTS) techniques.
Several majority carrier traps were consistently observed. The thermal stability of these centers was determined by isochronal annealing studies. Tentative identifications, based primarily on comparison with energy levels and thermal stability of defects previously observed in aluminum- or boron-doped and electron-irradiated silicon are as follows: E_v + 0.165 eV, Aℓ-related; E_v + 0.295 eV, vacancy + oxygen + boron; E_v + 0.39 eV, carbon-interstitial + carbon-substitutional; E_v + 0.71 eV, Fe-related. Samples irradiated at ∿290 K showed the energy level of the carbon-interstitial which anneals out at 300 K within a few hours and at the same time the carbon-interstitial + carbon-substitutional peak grows, which confirms that peak identification.

1. INTRODUCTION

Several different crystal growth processes have been developed which permit the growth of crystals of predetermined shape, in particular flat ribbons. There is considerable current interest in silicon crystals grown in ribbon form because of the desire for production of very low cost solar cells for terrestrial applications. The edge-defined method (EFG, which stands for edge-defined, film-fed growth) [1,2] has significant potential for reduced cost per unit area of devices and efficiency ratings more than 14% have been already achieved in large area (∿50 cm^2) solar cells produced on silicon of this form [3].

The use of carbon dies in form of graphite coated with SiC in growth of ribbon silicon results in substantial concentration of substitutional carbon (C_s as high as $10^{18} cm^{-3}$) in this material, and boron, aluminum, iron and oxygen are also known to be major impurities. Typical dislocation densities are 10^3 to 10^4. Silicon-carbide particles and linear boundaries (twins or stacking faults) which are parallel to the ribbon edge can be present as well.

The sample material used here has diffusion lengths in the range of 30 to 70 μm, was doped with boron to a resistivity of approximately 1 Ωcm and contains aluminum with a concentration of about $10^{16} cm^{-3}$. Other impurity concentrations are not known.

2. EXPERIMENTAL DETAILS

Schottky barriers were fabricated on the samples by evaporation of an aluminum layer. Most of the diodes were then irradiated with 2 MeV electrons at ∿310 K to fluences of 10^{14}, 10^{15}, or $10^{16} cm^{-3}$. Some samples were irradiated at ∿290 K. The defects then present were studied using standard transient capacitance techniques (DLTS) with a double boxcar integrator and a lock-in amplifier over the temperature range of 80-325 K. Samples irradiated at ∿290 K were studied over the temperature range 80-270 K. Thermal stability of the defects was determined by isochronal annealing over the temperature range from 350 to 650 K (above 650 K the Schottky barriers deteriorated rapidly), or in the case of samples irradiated at ∿290 K by isothermal annealing at 300 K. The DLTS spectrum was measured after each stage of annealing. The samples were not biased during either electron irradiation or thermal annealing.

3. EXPERIMENTAL RESULTS

Figure 1 shows typical DLTS spectra due to majority carrier traps resulting from the electron fluences of 10^{14}, 10^{15} and $10^{16} cm^{-2}$ in these p-type samples irradiated at ∿310 K. We systematically observed [4] three deep traps, labelled H_1, H_2 and H_3, with measured electrical energy levels of E_v + 0.165 ± 0.005 eV, E_v + 0.39 ± 0.01 eV, E_v + 0.71 ± 0.02, respectively. A weak fourth trap (H_4) was observed near 170 K after the heaviest irradiation. This trap becomes much more prominent after annealing at about 430 K and its energy level is then measured as E_v + 0.295 ± 0.005 eV. The DLTS spectrum after anneal at 430 K, demonstrating particularly the growth of the H_4 peak with respect to the others is shown in Fig. 2.

Figure 3 shows typical results of isochronal annealing of a sample irradiated to $10^{16} cm^{-2}$. The sample was held at a given temperature 15 min., the DLTS spectrum was taken, and then it was annealed again at a higher temperature. The H_1

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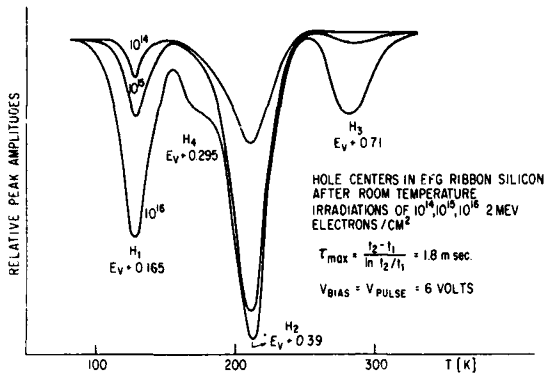

Fig. 1. DLTS spectra of boron-doped EFG ribbon silicon showing growth of majority carrier capture centers with electron irradiation at room temperature.

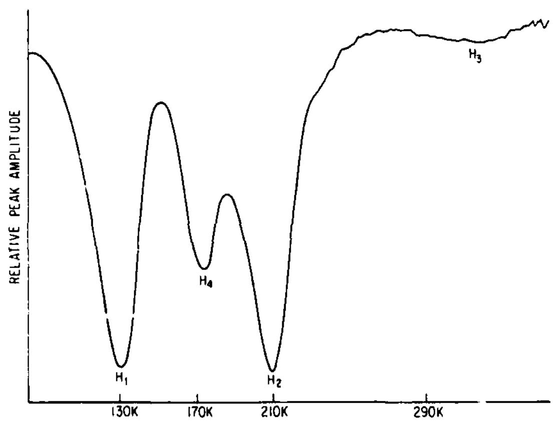

Fig. 2. DLTS spectrum of diode irradiated to fluence of 10^{16}cm^{-2} after isochronal anneal to 430 K, showing the growth of H_4 center with respect to centers initially present. Compare to Fig. 1.

peak remains approximately constant in amplitude over the entire temperature range. The largest peak H_2 begins to anneal just above 400 K and has entirely disappeared after anneal at 570 K. The small H_3 peak begins annealing between 350 and 400 K and is almost entirely gone after anneal at 430 K. The H_4 peak is growing rapidly with anneal at 430 K, continues to increase in size with anneal up to 500 K, and then anneals out rapidly between 550 and 600 K. Above 650 K the Schottky barriers deteriorate rapidly, so it is impossible to obtain any data at higher temperatures.

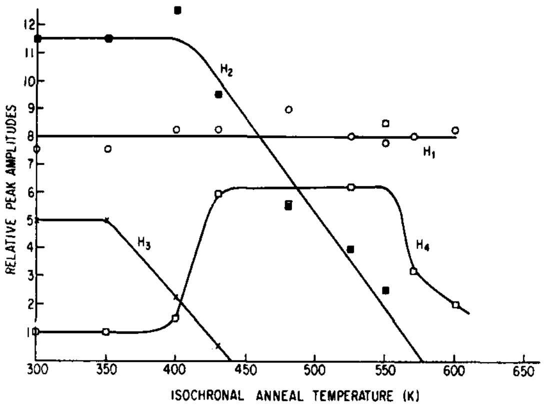

Fig. 3. Results of isochronal anneal of EFG ribbon silicon irradiated to a fluence of 10^{16} e/cm^2. (15 min. at each anneal temperature.)

Figure 4 shows a DLTS spectrum after electron fluence of 3 x 10^{15}cm^{-2} at ∿290 K. We observe two major traps labelled as H_1 and H_5. The H_1 is the same trap which we observe for irradiation at ∿310 K. The H_5 with its energy level measured as E_V + 0.30 eV decreases quickly and almost disappears in 6 h at 300 K, while the H_2 peak, the major trap for samples irradiated at ∿310 K, becomes visible in the spectrum.

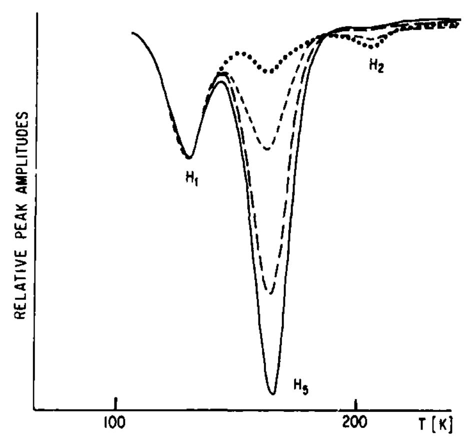

Fig. 4. DLTS spectra of irradiated to a fluence of 3 x 10^{15}cm^{-2} at ∿290 K diode showing isothermal annealing of H_5 at 300 K and the appearance of H_2. ——0, ---1, ----3, ...6h

Capture cross-section measurements were made for the most of these centers. We analyzed capture cross-section data in our previous paper [4].

4. DISCUSSION AND CONCLUSIONS

The tentative identification is based primarily on comparison with energy levels and the thermal stability of centers previously observed in aluminum-doped or boron-doped silicon which had been irradiated with electrons at near room temperature.

We tentatively correlate the H_1 peak at E_v + 0.165 eV, with an aluminum complex observed [5, 6] in aluminum-doped silicon. The H_3 center, at E_v + 0.71 eV observed only for relatively high fluences ($\geq 10^{15} cm^{-2}$) may be related to the iron impurity, as Schmidt [7] has observed an acceptor level in p-type silicon with iron at E_c - 0.55 eV. Our H_4 center, at E_v + 0.295 eV, demonstrates essentially the same annealing growth and decay characteristics as the E_v + 0.30 eV level observed by Mooney et al. [8] in boron-doped electron-irradiated silicon which was associated with a vacancy-oxygen-boron (V + O + B) complex.

The H_2 peak at E_v + 0.39 eV, which is the major peak after irradiation, we correlate with the carbon-interstitial + carbon-substitutional (C_i + C_s) pair identified by Brower [9], using EPR techniques, in electron-irradiated boron-doped silicon which contains carbon. Brower suggests that the pair is formed as a result of a mobile carbon interstitial being trapped by a substitutional carbon atom. It can be produced by either electron or neutron irradiation at room temperature [10].

Our correlation is supported by the very similar behavior under isochronal annealing, with both experiments showing the center disappearing at approximately 575 K. Isothermal annealing at 300 K shown in Fig. 4, confirms that peak identification as well. After irradiation at ~290 K we observe two major traps, the H_1, visible for irradiation at ~310 K, and the H_5, which i[s] present in the DLTS spectrum for irradiation at ~310 K. The H_1 peak which remains constant over the entire 300-650 K temperature range of isochronal annealing is predictably constant throughout the annealing period of 6 h at 300 K.

The H_5 peak at E_v + 0.30 eV, which anneals at 300 K, reveals the same characteristics as a positive charge state of the carbon interstitial (C_i) [11] which was observed by DLTS [12, 13]. The H_5 peak decreases quickly and almost disappears in 6 h while the H_2 peak which we correlate with (C_i + C_s) pair, simultaneously increases slowly after annealing for 3 h and 6 h at 300 K. The known high concentration of substitutional carbon in our samples, which is near solubility levels and much higher than in silicon grown by Czochralski and float zone methods, also supports our correlation.

Kimerling et al. [14] did associate a center which they observed at E_v + 0.36 eV, after proton bombardment, with the (C_i + C_s) pair, but its annealing behavior was similar to a center observed by Mooney et al. [8] at E_v + 0.38 eV which they associate with a vacancy-oxygen-carbon (V + O + C) complex after EPR identification by Lee et al. [15], and was probably the same center. Their center increases in concentration upon annealing to near 575 K and does not anneal out until 675 K, 100° higher than the center we observe.

The striking absence of a divacancy in DLTS spectrum supports the indirect formation of divacancies mechanism during room-temperature irradiation of silicon with 2 MeV electrons [16].

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[1]Present address: IBM Watson Research Center, Yorktown Heights, New York 10598, USA.

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